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CONCEPTUAL DESIGN OF A 150 kWe OUT-OF-CORE NUCLEAR THERMIONIC CONVERTER SYSTEM

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Abstract

Nuclear-thermionic systems with the thermionic converters outside the reactor have been re-examined in the perspective of several recent technical advances: new high-temperature, corrosion-resistant, high-strength alloys; high-heat-flux heat pipes; improved thermionic converters; and light-weight, vapor-cooled radiators. These have been combined to yield a new look to the out-of-core approach. A versatile, compact reactor results; insulators are eliminated by the use of heat pipes as electrically resistive elements; and weights are reduced by combining vapor-cooled radiators, structural supports, and current leads into vapor-cooled radiator modules. The over-all design is also highly modular and thus provides high reliability and a reduction in development time and costs.

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Introduction

Development efforts in thermionic energy conversion have become almost completely focused on the use of thermionic converters located in the core of a reactor. But recently several technological advances have stimulated new interest in out-of-core thermionics: improved thermionic converter performance at low emitter temperatures; development of high-strength, corrosion-resistant, ductile, refractory-metal alloys; new methods of refractory metal fabrication by chemical vapor deposition; development of high-temperature, high-throughput heat pipes;[1] new compact-reactor design concepts; the development of light weight multifoil insulation for high temperature use; and the evolution of light-weight vapor-cooled radiators. Some of these advances also benefit other space power systems, but the combination of the new technological advances exerts a unique impact on out-of-core thermionic concepts.

The direction of this study was thus established: apply the new technology to cope with problems of electrical isolation, use a reactor that is adaptable to a range of power levels as well as other conversion methods, and design a system that scales by modularity. The term modularity implies that the system is based on many small, identical, largely independent building blocks. The coupling of the building blocks must also adapt to modular, small-scale tests. Any advanced system will introduce engineering uncertainties, thus ease of testing and ease of scaling is emphasized.

The general design of the system presented in this paper was influenced by the approach used by Loewe.[2] It differs in that long heat transfer tubes (heat pipes) are used to provide electrical isolation between the converters and the heat source and a different reactor heat exchanger design approach is used. The preoccupation with modularity encouraged these changes.

This paper is similar to a design study of a 350 Kwe out-of-core thermionic system previously reported by Breitwieser and Lantz.[3] In this paper recent technological advances are reviewed in more detail, the groundrules which governed the study are discussed and the effect of reducing the power level of the out-of-core system to 150 Kwe is investigated.

Technology Review

In the early 1960's several comprehensive studies of out-of-core thermionic systems were conducted. In one of these studies performed by the General Electric Company under NASA sponsorship[4] two liquid metal pumped loop systems were considered; one in which the converters were located in the heat exchanger, and one in which the converters were located in the space radiator.

The liquid metal containment material considered in the study was columbium-1% zirconium (Nb-1Zr) which was made available in the late 1950's. A higher strength tantalum base alloy, T-111 (Ta-8W-2Hf) was in pilot plant production at the time of the study but was not considered because of limited knowledge of fabrication problems. The key issue in the study involved the achievement of reasonable converter performance while maintaining acceptable stress levels in the liquid metal containment materials. The strengths of Nb-1Zr and T-111[5] as well as the thermionic converter performance achievable in this time period, are illustrated in figure 1 where stress for 1% creep in 10,000 hours and electrode efficiency are plotted against temperature. Based on the Nb-1Zr strength the emitter temperature was limited to 2200° F. The study concluded that, based on the conversion efficiencies attainable at emitter temperatures on the order of 2200° F, out-of-core thermionic systems did not offer the potential of providing light-weight space power systems. Also the technology required for the electrical insulator between the liquid metal containment tubes and the emitter had not been developed. It was therefore recommended that the development of such a system not be initiated. For the following several years NASA-Lewis, as others, emphasized the in-core approach in an attempt to achieve the emitter temperatures required for acceptable system performance.

During the late 1960's a number of new technology items appeared. Much stronger tantalum base alloys than T-111 were developed, significant improvements in converter performance were made and the feasibility of the heat pipe was demonstrated.

Refractory metal alloy developments and converter performance improvements are considered in figure 2 where again, stress for 1% creep in 10,000 hours[5] and electrode efficiency has been plotted against temperature. The data from figure 1 has been included for reference. As shown, the 811-C alloy (Ta-8W-1Re-1Hf -0.025C), developed in 1965, exhibits a much higher creep strength than T-111 at a given operating temperature and the tantalum alloys having higher tungsten content, 12 to 18%, offer a factor of 3 to 4 advantage in strength over 811-C. Thermionic conversion efficiency has also improved significantly since 1962 with

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electrode efficiencies as high as 18% calculated from 1969 performance data.[6] The overlap in material strength and converter performance is very much in evidence today so that out-of-core operation at an emitter temperature of 2600° F and possibly even 2800°F at corresponding electrode efficiencies of 15 to 18% can be considered.

The heat pipe, which has proven to be an extremely efficient heat transfer device, has also been developed to the point where it can be considered for inclusion in a power system. Some of the test results obtained with lithium heat pipes are summarized in Table 1. The maximum heat transfer values demonstrated experimentally include a radial heat flux of 170 watts/cm^2 of lateral surface area[7] and an axial heat flux of 15,000 watts/cm^2 of cross sectional area.[7] It should be noted that, although these values are extremely high, they were limited by the experimental equipment available and are below the calculated theoretical limits.

In regard to life, a TZM (Mo-0.6Ti-0.1Zr-0.025C) clad pipe was operated at a radial heat flux of 20 watts/cm^2 for over 10,000 hours at 1773° K.[8] The pipe failed due to a leak in an end cap weld, however post test analysis indicated that the leak was not corrosion related but was due to the brittle nature of the alloy. A tungsten-26% rhenium pipe has been operated for over 6000 hours at 1873° K with a radial heat flux of 100 watts/cm^2 and this test is continuing.[9] Turning now to more ductile clad materials, a tantalum heat pipe was operated at a heat flux of 170 watts/cm^2 for 1000 hours at 1875° K.[7] This pipe did not fail and subsequent post test metallurgical examination indicated no significant corrosion. Admittedly, there are very few data points related to heat pipe life but indications are that lithium heat pipes can be operated for long periods of time at elevated temperatures and at heat fluxes which, as will be shown later, are representative of the out-of-core thermionic application.

Sodium vapor chambers, appropriate for converter cooling, have been successfully operated at 1300° F by the General Electric Co. (stainless steel clad)[10] under NASA contract and in an in-house program at Lewis Research Center (Nb-1Zr clad). To date the Nb-1Zr vapor chamber has accumulated 1250 hours of test time at 1000° K.

One item, considered critical to the success of an out-of-core system in the early 1960's, that was not developed during the latter part of the decade, was the high temperature ceramic insulator. However, as will be illustrated later, a long, thin-walled heat pipe is an effective electrical insulator.

The technology developments described above lead to a reassessment of the potential of out-of-core thermionics and an internal Lewis study of such systems was initiated in early 1970.

Study Ground Rules

It should be recognized that constraints are placed on system selection by the set of groundrules which govern such items as mission applications, reliability requirements, ease of development, etc. The groundrules selected for consideration are summarized in Table II.

The concept of a compact, multipurpose reactor suggests that a single reactor be developed to meet a variety of mission requirements. These, of course, include missions which require only instrument-rated shielding as well as missions which would require complete 4π shielding for manned application; hence emphasis is placed on a minimum size reactor. Since a major manpower and dollar investment is involved in reactor development the possibility of developing a single advanced reactor for a variety of conversion systems was examined. It was determined that the multipurpose reactor groundrule could be extended to accommodate thermionic, Brayton, Rankine and thermoelectric conversion systems. For the dynamic and thermoelectric systems the power conversion equipment operates at much lower temperatures than required for thermionics but an adjustment of the temperature drops in an intermediate heat exchanger can be made to easily accommodate the lower temperature systems.

In adopting a straightforward modular approach to system development provision is made for redundancy of basic modules and, by proper design, failures can be made nonpropagating. That is, a failure of a single component or group of components need not lead to failure of the complete system. This is particularly important in relation to manned missions where multiple failures must be sustained while still guaranteeing the safety of the crew. In addition, such an approach results in additional benefits due to low module fabrication costs, low cost tests, and short turn around times for redesign and reevaluation of modules.

The electrical output power range considered is 70 to 400 kilowatts. At the lower power level, of interest for unmanned electric propulsion missions, both uranium atom burnup and heat fluxes are quite modest. Since the so-called compact reactor would be criticality limited the thermal power can be readily adjusted by increasing the burnup and heat flux. However, neither maximum burnup levels nor maximum heat fluxes for lithium-filled heat pipes have been experimentally established as yet, so that the system growth characteristics cannot be accurately predicted. In view of these facts a reevaluation of the maximum electrical power that can be achieved with a fixed reactor design must be made when appropriate data becomes available.

System Description

Factoring in a thorough evaluation of the groundrules described above as well as the technology developments achieved over the past several years in refractory alloys, converter performance and heat pipes an all heat-pipe out-of-pile thermionic system was selected for further study. The system consists of a heat pipe cooled reactor, and a modular, heat pipe heat exchanger from which thermal energy is carried to the space radiator where the converters are located. The heat pipes that run from the heat exchanger to the radiator are also used as resistive elements in place of a ceramic insulator. Each converter is cooled directly by radiation to space from a vapor chamber fin. The system components are described below:

Reactor - Heat Exchanger

A heat pipe cooled, vented, fast-neutron, reflected, reactor, shown schematically in figure 3, was assumed in this study. Heat pipe cooling was selected from the standpoint of both modularity and reliability. A number of the nucleonic and heat transfer features of heat pipe cooled reactors that are quite similar to the one considered herein are discussed in reference 11. Therefore, only a brief reactor discussion will be included. For the specific design selected, a uranium carbide fuel volume fraction of 0.53 was calculated.

A split reactor is assumed with criticality control achieved by relative motion of the halves. Electrical isolation of the two halves can also be readily accomplished which will, as shown later, lead to an increase in system output voltage.

A total of 163 heat pipes exit from each half of the reactor. The reactor heat pipes can be fabricated by chemically vapor depositing tungsten on molybdenum mandrels which are subsequently removed by acid etching. Lithium, at a vapor temperature of 1850° K, is the working fluid. In the reactor the heat pipes are of cylindrical cross section and transform to a rectangular cross section outside the core (see fig. 4). The hexagonal tungsten radial reflector section is vapor deposited in place when the heat pipe is made. The cylindrical evaporator section of each heat pipe is 1.27 cm, 0.5 in., in diameter and 11.5 cm, 4-3/8 in. long; the reflector section is 5 cm long and the condenser (heat exchanger) section is 1.27 cm, 0.5 in., by 2.66 cm, 1.05 in., by 10 cm, 3.94 in., long. At the 150 Kwe system output power level and a system efficiency of 10.4% (System Performance section) the nominal evaporator heat flux is 97 W/cm^2. The nominal axial heat flux is 5.8 kw/cm^2. These nominal heat flux calculations were based on a uniform volume heat generation rate in the core. Since no attempt to flatten the power distribution was made the peak evaporator heat flux would be on the order of 136 W/cm^2 (1.4 times the nominal value while the peak axial throughput would be 6.95 kw/cm^2 (1.2 times the nominal value). However, even the peak values are below the maximum values demonstrated experimentally (Technology Review section).

The heat pipes that extend from the reactor core form the walls of a modular, flat-plate, cross flow heat exchanger. The heat exchanger is completed by inserting the flattened ends of tantalum alloy heat pipes, at the opposite end of which the converters are arranged, in a multilayered fashion as shown in figure 5. Thermal contact between the tungsten and tantalum alloy walls is maintained by an external hoop that surrounds the heat exchanger. One of the unique features of this heat exchanger is the accommodation of local failures of either reactor or converter heat pipes since both modularity and multilayering are used.

The reactor-heat exchanger assembly is quite compact; the reactor core is 32 cm, 12.6 in., in diameter and 23 cm, 9.1 in., long while the overall assembly is 46 cm, 16.4 in., in diameter, including a 7 cm, 2.75 in., thick radial reflector, and 53 cm, 20.9 in., long.

Converter Heat Pipes

The tantalum alloy converter heat pipes extend from the heat exchanger to the radiator station, a distance of approximately 12 ft. in a 150 Kwe system design. The length in this particular design was established by radiator area requirements. This 12 ft. section of each converter heat pipe, referred to as the adiabatic section, is thermally insulated with refractory metal, multifoil insulation to minimize heat losses and also is armored against meteoroid penetration. A total of 84 converter heat pipes each carrying 17.2 Kw of thermal energy are required. The pipes are 0.60 inch in diameter, have a 0.030 inch wall thickness and operate at an axial heat flux of 13.1 kilowatt/cm^2; again a value that has been exceeded experimentally. In the converter heat pipe analysis, a lithium vapor temperature of 1800° K was assumed and the hoop stress in the containing walls was limited to 450 psi.

Upon leaving the heat exchanger the pipes are physically separated, providing electrical isolation between the converters and the heat source. It is interesting to observe that the electrical resistance of a long heat pipe is relatively high. The use of long heat pipes as resistive elements in place of ceramic members, as shown in fig. 6, is discussed in detail in reference 12. The calculations show that the electrical leakage loss for a 12 ft. long pipe array, for which a system output voltage of 16 volts is assumed, is approximately 8% of the generated power.

Converter - Radiator

The converter design proposed for the system is shown in figure 7. The converter design and test results achieved with prototype converter components are described in detail in references 13 and 14.

Salient features of the converter are:

1. An oriented (0001 Miller index) chemically-vapor deposited rhenium emitter.
2. A niobium collector spaced 9 mils from the emitter.
3. A compacted cermet (made of Al_2O_3 coated niobium spheres) insulator.
4. A sodium filled compartmented, vapor fin radiator 44 cm (17 inches) long.

The design permits pretesting of the converter and integral radiator by electron bombardment heating. After pretesting the converter is shrunk onto the tantalum base alloy heat pipe. Five converters each 14.0 cm long form a complete heat pipe bank producing 1.8 Kwe. The heat pipes and converter bank can be pretested prior to assembly.

System Performance

System weight and efficiency estimates at the 150 Kwe level are presented below. Included are the weights of the primary system components; the reactor, instrument-rated shield (10^{12} nvt and 10^7 rad at 100 ft. within a 10° half-cone angle), converter heat pipes, thermal insulation and armor for the converter heat pipes and the integral converter-radiator. The reference converter-radiator weight and system efficiency are based on the single crystal rhenium-niobium data of reference 15. Also included are system efficiency and component specific weights based on the higher, tungsten-niobium performance data of reference 6.

In general, the specific weights of the components are quite modest. As a matter of fact the lower converter-radiator specific weight is about the same as the weight of a bumper fin radiator recently estimated for an advanced (2100° F) Rankine cycle power system[16] yet it also contains the power conversion devices. The total weight of the power system would, of course, exceed the sum of the primary component weights. However, additional weights for ancillary equipment have not been included since they are so strongly interrelated with specific missions.

We note that, to a certain extent, this paper advocates a new compact heat-pipe cooled reactor design based on modular elements that reduce development costs and time, and possess a large amount of redundancy for system reliability. Fortunately, this reactor design adapts to most external conversion techniques.

The potential reliability of this modular reactor lends itself quite naturally to high temperatures. And in the framework of new performance improvements of thermionic conversion we can project an integral radiator, thermionic-converter design that weighs about the same as the radiator alone of competitive systems. Perhaps most important of all, modularity is retained all the way to the point of heat rejection if out-of-core thermionics are used.

Concluding Remarks

Recently a combination of engineering advances has brought about a revival of interest in out-of-core thermionics. Information on corrosion, strength of materials, vapor-phase heat transfer, improved converter performance and reactor-fuel stability has been combined to make some of the old concepts more attractive. But of more importance, the new information has stimulated innovative approaches. Coupled with new concepts in modular design and testing, out-of-core thermionics may provide an effective, reliable, multipurpose power plant.

The space power system suggested in this paper is a deliberate attempt to move system designers and potential users away from their usual patterns. Split reactors, metal tubes used as insulators, small-bore reactor heat pipes, decoupled components, flexible configurations, and simple assembly procedures were approaches used. Although the particular system illustrated may have its faults, out-of-core thermionics using the advanced technology of the 1970's should prove to be a strong contender for nuclear-space power.

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TABLE I

Heat Pipe Performance

LITHIUM

Heat Flux (maximum values demonstrated)

Radial - 170 watts/cm^2

Axial - 15,000 watts/cm^2

Life

Clad Material	Temperature °K	Radial Heat Flux Watts/cm^2	Time Hours
TZM	1773	20	10,000+
W-26 Re	1873	100	6,000
Ta	1873	170	1,000

+ Failed due to leak in end cap weld

SODIUM

Na-Nb-1Zr vapor chamber fin operating at 1000° K

Na - stainless steel vapor chamber fin tested at 1000°K

TABLE II

System Selection Groundrules

1. Compact, multipurpose reactor.
2. Modular approach.
3. 70 - 400 kilowatt power level.

TABLE III

150 Kwe In-Radiator System Performance

	Re-Nb	W-Nb
Emitter Temperature	1780°K	1780°K
Collector Temperature	933°K	923°K
Electrode Efficiency	14.1%	15.6%
System Efficiency	10.4%	11.9%

Item	Specific Weight - lb/Kwe Re-Nb	Specific Weight - lb/Kwe W-Nb
Reactor	10.5	10.5
Instrument Shield	17.1	17.1
Converter Heat Pipes Insulation and Armor	5.0	5.0
Converter - Radiator	10.9	9.7

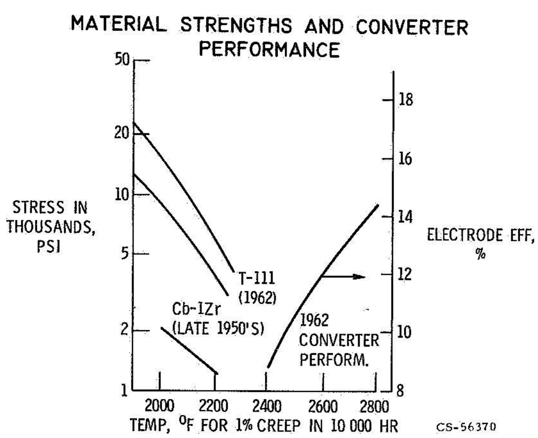


Figure 1

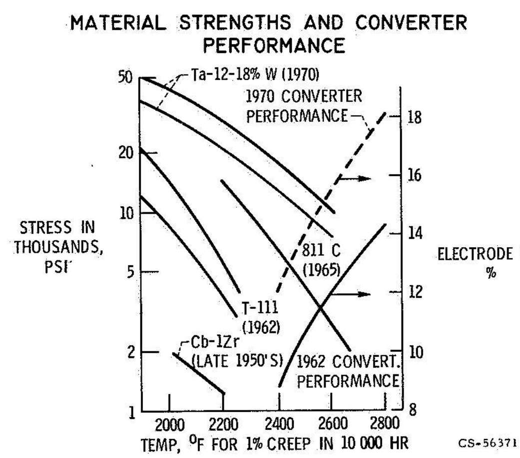


Figure 2

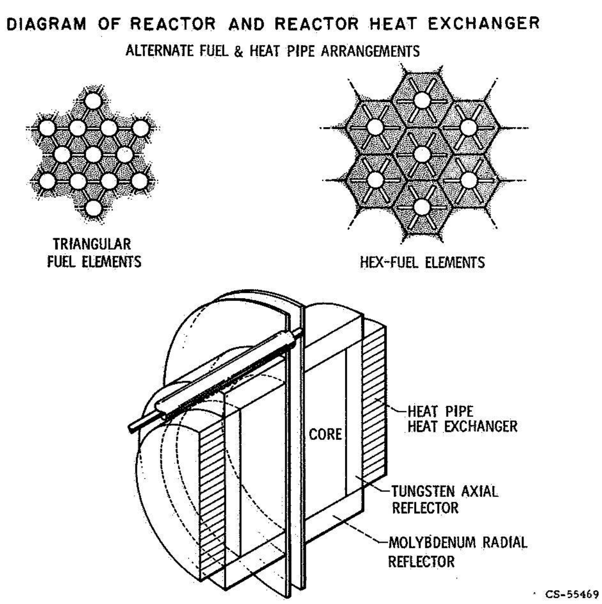


Figure 3

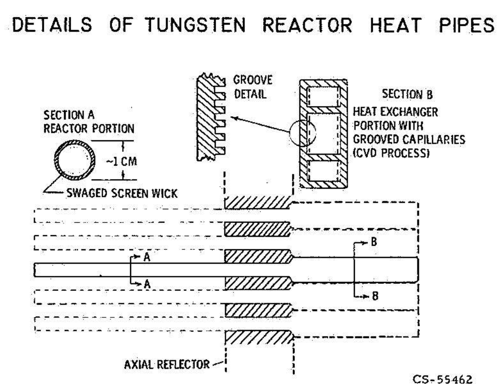
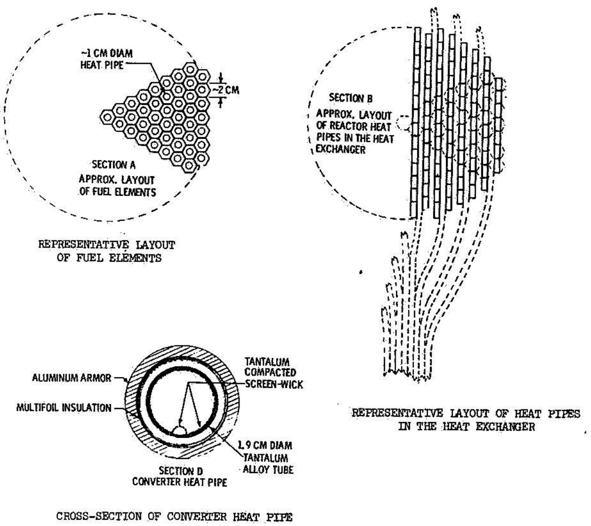


Figure 4



SCHEMATIC ARRANGEMENT OF FUEL ELEMENTS AND HEAT PIPES

Figure 5

AN EXAMPLE OF HOW HEAT PIPES CAN BE USED FOR ELECTRICAL ISOLATION

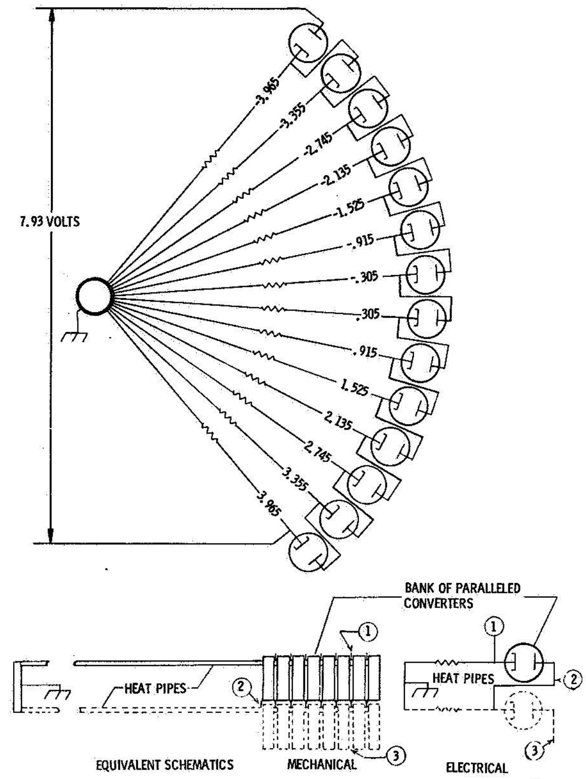


Figure 6

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THERMIONIC CONVERTER AND INTEGRAL VAPOR FIN RADIATOR

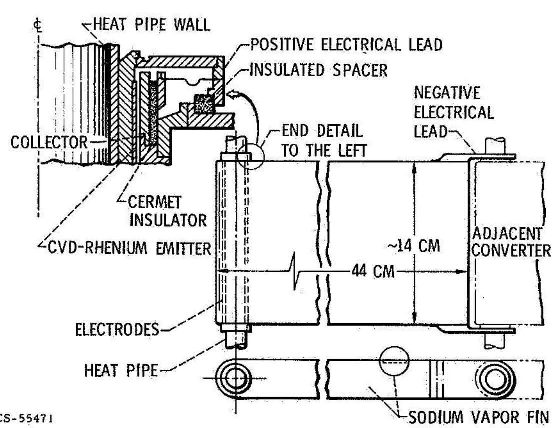

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Figure 7

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